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METHOD AND APPARATUS FOR DAMPING MECHANICAL OSCILLATIONS OF A SHAFT IN MACHINE TOOLS, MANUFACTURING MACHINES AND ROBOTS

of which the following is a complete specification:

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CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims the priority of German Patent Application, Serial No. 102 46 093.0, filed October 2, 2002, pursuant to 35 U.S.C. 119(a)-(d), the disclosure of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] The present invention relates to a method and apparatus for damping mechanical oscillations of shafts of a machine tool, manufacturing machine or robot by providing feedback elements that apply a negative feedback output signal from each feedback element to the desired rotational speed value of a speed controller for a motor driving the shaft.

[0003] Modern machine tools, manufacturing machines or robots frequently produce undesired oscillations, particularly about the shafts and in particular the NC-shafts (numerical-control shafts) of the machine. It is to be understood by persons skilled in the art that the term "machine" is used here in a generic sense and the principles described in the following description with respect to machine are equally applicable to robots. The oscillations are caused by poorly damped mechanical resonances in the mechanical system of the machine. As a result, the speed of the shaft is increased above or reduced below the point where the undesired resonance occurs. Such resonance produces undesirable chatter marks that mechanically strain the machine, and leads to a decrease in the processing accuracy. As a rule, the mechanical system of the machine has several areas of resonance, which have respective limited frequency ranges.

[0004] In a conventional drive controller, a superordinated position-control circuit provides a desired motor speed to a subordinated speed controller for rotation of the machine shafts. In the event a respective gain is selected for the speed controller, the mechanical resonances of the mechanical system of the machine are clearly noticeable in the form of drops and increases in the amplitude excursions of the reference frequency response in the speed control circuit. Only a very limited damping of these resonance oscillations is possible with the position control means available. This conventional approach is unsuitable for implementing an effective damping of the oscillations caused by mechanical resonance. The result is inadequate machine dynamics and chatter marks, as well as the gain in the position controller being limited to just a small adjustable range.

[0005] German Pat. No. DE 196 20 439 C2 discloses a method of damping mechanical oscillations in machine tools and robots, saw-tooth oscillations in particular, as well as rotational oscillations. Two control variables are determined by two acceleration detectors and fed back via the controller to a drive controller as a desired value.

[0006] It would therefore be desirable and advantageous to provide an improved method and apparatus of damping mechanical oscillations, to obviate prior art shortcomings and to exhibit limited oscillation frequency ranges for shafts of machine tools, manufacturing machines or robots, while being simple and cost-efficient.

SUMMARY OF THE INVENTION

[0007] According to one aspect of the present invention, a method of damping the mechanical oscillations of at least one shaft in a machine tool, manufacturing machine or robot, includes the steps of measuring an actual position value of a shaft using at least one sensor and/or measuring system, determining an actual speed of the shaft from the actual position value through differentiation, supplying the actual speed of the shaft as an input signal to each of a plurality of feedback elements, with each feedback element providing an output signal from each of the feedback elements that is negatively coupled and applied to a desired speed signal of a motor speed controller for the motor driving the shaft, and tuning each of the feedback elements to a specific oscillation frequency range of the oscillations of the shaft that are to be damped.

[0008] According to another feature of the present invention, tuned band-pass or high-pass elements tuned to the respective oscillation frequency range to be damped can be used as feedback elements. Band-pass or high-pass filter elements can easily be implemented using typical mathematical calculation programs in use today. The filter is constructed so as to provide a suitable gain and phase margin in the oscillation frequency range that is to be damped. This determines the range of frequencies that are controlled.

[0009] According to another feature of the present invention, a differential element tuned to the respective oscillation frequency range to be damped and having a first-order (DT1) or a differential element having a second-order (DT2) or a higher-order delay can be used. DT1-elements, DT2-elements and differential elements of a higher order, are able to differentiate below a limit frequency and to provide an adequate phase margin in a closed control circuit, thereby protecting the stability of the control circuit. In some instances, it is advantageous if the delay of second-order or higher-order has a slight damping effect and thus produces a rise in the resonance.

[0010] According to another feature of the present invention, instead of using the sensor and/or measuring system for measurement of the actual shaft position value, a sensor and/or measuring system can be used for measurement of the shaft acceleration, or the acceleration is determined by second-order differentiation from the shaft position value. The acceleration is then used as an input variable for the respective feedback element. Resonance oscillations are especially easy to detect in the acceleration of the shaft. Acceleration can advantageously be directly measured on the shaft or areas which are caused to oscillate as a consequence of a shaft movement.

[0011] According to another feature of the present invention, a proportional element tuned to the respective oscillatory frequency range to be damped and having a first-order delay or a second-order or higher-order delay can be used as a feedback element. Of course, it is also possible to calculate the speed of the shaft from the acceleration by integration and then to use as feedback elements the DT1-elements, DT2-elements and differential elements having a higher-order delay. A drawback of this approach is, however, an increase in computation time compared to a direct processing of the shaft acceleration in the feedback elements. In certain cases, however, this approach may still be advantageous, for example when the use of proportional elements is undesirable.

[0012] According to another feature of the present invention, instead of a sensor and/or measuring system for measuring position values for the shaft, a sensor and/or measuring system may conceivably be used as well, for measuring the actual speed of the shaft. The actual speed of the shaft is then fed directly to the feedback elements as an input variable. The determination of the actual shaft speed by differentiation of the actual position value of the shaft can thus be eliminated by directly measuring the actual speed.

[0013] According to another feature of the present invention, in addition to or instead of the sensor and/or measurement system for measurement of the actual shaft position, further sensors and/or measurement systems can be used, especially those for measuring shaft acceleration and/or shaft speed, and the respective measured shaft variable or a calculated variable produced from measured variables is supplied as input variable to a respective one of sets of feedback elements, whereby each of the sets of feedback elements has at least one feedback element. By the use of not just one but multiple measured variables as input variables for a respective separate set of feedback elements, for example an actual position value as well as shaft acceleration, a particularly good damping of the mechanical shaft oscillations can be achieved.

BRIEF DESCRIPTION OF THE DRAWING

[0014] Other features and advantages of the present invention will be more readily apparent upon reading the following description of currently preferred exemplified embodiments of the invention with reference to the accompanying drawing, in which the sole FIG. 1 is a schematic block diagram illustrating the components of the subject matter of the present invention:

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0015] The depicted embodiment is to be understood as illustrative of the invention and not as limiting in any way. It should also be understood that the drawings are not necessarily to scale and that the embodiments are sometimes illustrated by graphic symbols, phantom lines, diagrammatic representations and fragmentary views. In certain instances, details which are not necessary for an understanding of the present invention or which render other details difficult to perceive may have been omitted.

[0016] Turning now to FIG. 1, there is shown a schematic block diagram illustrating the components of the subject matter of the present invention. A motor 1 drives a not shown shaft of a machine via a mechanism 2. An actual speed V_{m_actual} of the motor 1 and an actual position value X_{p_actual} is measured by a suitable measuring system. The motor speed V_{m_actual} is controlled by a motor speed controller 3, which has the difference between the motor speed V_{m_actual} and the desired motor speed $V_{m\_desired}$ as an input variable E and on the output side provides a control output signal A to a motor controller 4 that controls the motor speed V_{m_actual} through an output current I.

[0017] The motor speed controller 3 may be implemented as a conventional proportional integral-action controller. A desired motor speed position value $V_{p\_desired}$ is given by a superordinated position control circuit (not shown for ease of illustration) for position control of the shaft.

[0018] In the exemplified embodiment shown here three oscillation frequency ranges or resonance areas of the mechanical systems of the machine are assumed.

[0019] An actual shaft speed V_{p_actual} is calculated from the actual shaft position value X_{p_actual} by means of a differentiation element 5 and delivered to the feedback elements R1, R2, R3. The output signals B1, B2, B3 of the feedback elements R1, R2, R3 are negatively coupled and applied to a desired motor speed position value $V_{p\_desired}$, which is generated by a superordinated position control circuit (not shown for ease of illustration), to form on the output side a desired motor speed signal $V_{m\_desired}$.

[0020] A feedback element is provided for each oscillation frequency range to be damped. Thus, the assumed three oscillation frequency ranges to be damped in the present exemplified embodiment requires therefore three feedback elements R1, R2, R3. FIG.1 illustrates the parallel control structure and feedback structure, respectively. To suppress even more oscillation frequency ranges or resonance areas, the arrangement shown is supplemented by further feedback elements or feedbacks connected in parallel and tuned to the respective oscillation frequency ranges to be damped.

[0021] When selecting suitable feedback elements, care should be taken to provide them with a suitable gain and phase margin in the range of the oscillations that are to be suppressed. Such a feedback element can readily be realized as a band-pass filter or a high-pass filter, for example, in the form of a finite impulse response or an infinite impulse response filter. Suitable filters can be easily calculated today, or the filter coefficients defined, using commercially available filter design programs. In the design of the feedback element, care should be taken so that the phase margin in the closed control circuit is not too small, otherwise the stability of the control circuit is jeopardized.

[0022] An example for use as feedback elements with band-pass response includes differential elements with second-order delays, so-called DT2 elements, which have a transfer function in the form:

$$R(s) = \frac{s}{T^2 s^2 + 2dTs + 1}$$

wherein the parameter "*s*" relates to the complex circuit frequency while the frequency behavior of the DT2 element can be parameterized with the assistance of the time constant "*T*" and the damping "*d*".

[0023] Examples for the transfer function of high-pass filters include:

$R(s) = \frac{s}{Ts+1}$ or $R(s) = \frac{T_2^2 s^2 + 2 d_2 T_2 s + 1}{T_1^2 s^2 + 2 d_1 T_1 s + 1} - 1$

wherein

T is the time constant,

T_1 is the denominator time constant,

T_2 is the numerator time constant,

d_1 is the denominator damping value, and

d_2 is the numerator damping value.

[0024] The parameter s relates hereby to the complex circuit frequency while the time constants T, or T_1, T_2, d_1 and d_2 are used to parameterize the frequency behavior of the high-pass elements. Feedback elements of this type operate in lower frequency ranges by differentiation, i.e., they display high-pass characteristics and allow an adequate phase margin for the control circuit.

[0025] Of course, other feedback elements may also be used. In the exemplified embodiment of FIG. 1, the feedback elements R1 and R2 are realized as band-pass elements, while the feedback element R3 is implemented as differential element DT1 having a first-order delay.

[0026] For specific phase margins it may be necessary to include additional filters in the feedback element, for example low-pass or notch filters.

[0027] The parallel control structure shown provides easy set up of the mechanism. Initially feedback elements can be deactivated, the feedback elements R2 and R3 for example. Only the feedback element R1 is activated, and correspondingly parameterized. Once the feedback element R1 has been parameterized, the feedback element R2 is additionally activated and parameterized. Activation and parameterization of the feedback element R3 follows thereafter.

[0028] Instead of taking the actual shaft position X_{p_actual} as feedback value, it is also possible to use suitable sensors or measuring systems to directly measure shaft acceleration, or to use the directly measured actual shaft speed V_{p_actual}. If the acceleration is selected as the input variable in place of the actual shaft position X_{p_actual}, then the actual shaft speed V_{p_actual} can be calculated through integration, and supplied to the feedback elements or, in the event that the provision of an additional integrator is not desired, proportional elements (PT1) having first-order delay, or proportional elements (PT2) having second-order delay can be used in place of the DT1 or DT2 feedback elements, and the measured acceleration can be supplied directly to the PT1 or PT2 elements. The transfer functions of such elements are well known in the art, and therefore a further discussion thereof is omitted for the sake of simplicity.

[0029] Instead of an explicit measurement of the acceleration of the shaft, it is also conceivable to calculate the shaft acceleration through second-order differentiation of the actual position value X_{p_actual} and to subsequently supply it as input variable to the PT1 elements or PT2 elements.

[0030] If the actual shaft speed V_{p_actual} is taken as the input value in place of the actual position value X_{p_actual}, the differentiating element 5 can be eliminated.

[0031] Of course, it is not necessarily required to use only one measurement variable, e.g. actual position value, actual speed and acceleration of the shaft, as input variable of the control elements; Rather, it is also possible to use, e.g. actual position value and acceleration of the shaft simultaneously as controlled variables, or variables calculated therefrom as input variables. The actual position value of the shaft is, for example, supplied to a first set of feedback elements as input variable, and the acceleration is supplied to a second set of feedback elements as input variable. A set of feedback elements is hereby comprised of at least one feedback element. Basically, any desired combination of input variables is possible.

[0032] Furthermore, the parallel control structure depicted allows a simple set up of the machine. For example, the feedback elements R2 and R3 can initially be deactivated, with only feedback element R1 activated and correspondingly parameterized. Once the feedback element R1 has been parameterized, the feedback element R2 is additionally activated and parameterized. Activation and parameterization of the feedback element R3 follows thereafter.

[0033] While the invention has been illustrated and described in connection with currently preferred embodiments shown and described in detail, it is not intended to be limited to the details shown since various modifications and structural changes may be made without departing in any way from the spirit of the present invention. The embodiments were chosen and described in order to best explain the principles of the invention and practical application to thereby enable a person skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated.

[0034] What is claimed as new and desired to be protected by Letters Patent is set forth in the appended claims and their equivalents: